Irrig Sci (1994) 15: 35–44

ORIGINAL PAPER

M. Susan Moran

Irrigation management in Arizona using satellites and airplanes

Received: 28 October 1993

Abstract Agriculture has long been promoted as a prime beneficiary of remotely sensed data and satellite data are now routinely used in crop production forecasts and for resource surveys. However the potential for using satellite data for irrigation management has not been realized. An experiment was conducted at the Maricopa Agricultural Center, Arizona, to test the feasibility of using satellite and aircraft data for crop monitoring and irrigation management. This experiment identified several shortcomings of present satellite systems with respect to providing timely information for irrigation management. On the other hand, a preliminary evaluation of aircraft data showed some potential for application to irrigation scheduling. A simple cost/benefit analysis suggested that profits could be achieved through the communal use of remotely sensed information from both satellites and aircraft in moderate-size irrigation districts.

Introduction

It has been 25 years since A. Park and others from the USDA Agricultural Research Service and the U.C. Berkeley School of Forestry outlined a scenario for "resource survey by satellite" (Park et al. 1968). In this scenario, a hypothetical agronomist and forester managed 800,000 acres of forest and irrigated agricultural land using a computer-based decision support system for analysis of aircraft- and satellite-based spectral images. Among other things this system allowed the managers to schedule crop irrigations and verify irrigation efficiency by monitoring crop growth patterns and anomalies. In this scenario, the managers reviewed six months of weather and surface information in a single two-hour session and identified several management problems associated with insect infestation and misapplication of herbicide. At the end of the session, the forester commented, "With this new technology, we have the most powerful management tool to come out of research during the last 50 years."

Sixteen years later, Jackson (1984) evaluated the state-of-the-art concerning relations between spectral data and crop/soil properties and detailed the requirements for a farm-oriented remote sensing system. He found that two decades of research using ground- and aircraft-based sensor systems have documented that remotely sensed information would be valuable for making day-to-day farm management decisions such as irrigation scheduling, disease detection and crop condition. Yet, he concluded with some disappointment that, "It is time to fulfill the promises of the past quarter century." Considering that the technology described by Park et al. (1968) has been available for over 25 years and the system requirements suggested by Jackson (1984) are ten years old, it is time to revisit this scenario and evaluate our progress toward this goal.

The evaluation presented here differs from that of Jackson (1984) in that it is not a review of research progress, but rather, presents results from a field experiment designed to evaluate current satellite systems for near real-life farm management. The overall success of the experiment was assessed by addressing two independent objectives: 1) the evaluation of the utility of *current* satellite-based systems (specifically, SPOT HRV and Landsat TM) for irrigation management; and 2) the evaluation of aircraft-based spectral data for use in irrigation scheduling.

Experimental methods

The idea for this experiment originated at the Institute for Technology Development (ITD), Space Remote Sensing Center, Mississippi. The objective was to evaluate the use of satellites for day-to-day farm management by obtaining every possible SPOT and Landsat scene over a summer growing season. At the onset, it was recognized that deliv-

M. S. Moran (✉)
U.S.D.A. Agricultural Research Service,
U.S. Water Conservation Laboratory,
4331 E. Broadway Rd.,
Phoenix, AZ 85040, USA;
Fax no: (6 02)-6 70-64 93

ery of the data would be too slow for optimal real-time use, but management decisions were to be made in retrospect and compared with real-time decisions based on observations and experience. Satellite data would be obtained and processed on-farm, and the information would be provided directly to farm managers for interpretation (with a maximum two week time lag). During each satellite overpass, a low-altitude aircraft would be deployed to acquire multispectral video data which would be processed and shown to the farm manager on that same day.

To implement this experimental design ITD personnel approached scientists at the U.S. Water Conservation Laboratory (USWCL) and the University of Arizona (UA). These scientists agreed to cooperate and expanded the ITD objectives to include personal research goals, including analysis of the effects of sun/sensor/target geometry and atmosphere on signal response, and occasional in-flight calibration of satellite sensors.

The site for the experiment was the Maricopa Agricultural Center (MAC), a 770 ha research and demonstration farm located about 48 km S of Phoenix, owned and operated by the University of Arizona. The demonstration farm is ideal for large-area remote sensing research, with fields up to 0.27×1.6 km in size used for demonstrating new farming techniques on a production scale. Alfalfa is grown year-round with about 7–8 harvests per year; cotton is grown during the summer, and wheat during the winter. A data management system is in place to archive planting and harvesting information, and the times and amounts of water, herbicide and pesticide applications. The predominant irrigation method for the MAC demonstration farm is flooding. Sections of the field are flooded with a 3–4 day progression from one end of the field to the other.

The first step in the experimental design was to compute the dates of Landsat and SPOT overpasses during 1989. Over a potential 200-day growing season, there were 95 possible SPOT High-Resolution Visible (HRV) and Landsat Thematic Mapper (TM) acquisitions with a maximum time lapse between acquisitions of 5 days. This schedule of image acquisitions was computed by including both the Landsat4 and Landsat5 TM sensors and all possible viewing angles of the SPOT1 HRV1 and HRV2 sensors. Arrangements were made with EOSAT Corp. and SPOT Image Corp. to acquire all these scenes, with the understanding that they would be informed immediately after the overpass to let them know if we wanted to purchase the scene. EOSAT Corp. and SPOT Image Corp. agreed to send the images on magnetic tape directly to MAC with a two-week delivery schedule. For the most intensive management period (June–July), an ITD technician was assigned to MAC to conduct data processing and image analysis tasks. For the remainder of the experiment, he was assigned to ITD in Mississippi to process the satellite products.

During each satellite overpass, an aircraft was deployed at a nominal above-ground altitude of 100 m along a flight line traversing the center of each MAC field. In addition to the multispectral video camera, a nadir-looking, 15° field-of-view Exotech 4-band radiometer and Everest infrared thermometer (IRT) was mounted on the aircraft to measure surface reflectance and temperature. A small data logger collected a sample signal every second and recorded the time of sampling to 0.0001 h. The flight was scheduled to bracket the time of the satellite overpass (Landsat or SPOT). During the flight, each field was traversed before and after the overpass so that data from the two transects could be combined to provide an average value corresponding to the precise time of the satellite image acquisition.

During most overpasses surface reflectance and temperature was measured over limited areas of selected fields using ground-based radiometers. Periodically, a ground crew measured crop leaf area index (LAI) and soil moisture content in several fields using standard methods. Details about the methods and instrumentation used in this and similar MAC experiments have been given by Qi et al. (1993), Moran et al. (1990) and Pinter et al. (1990).

Results

The logistical results of the experiment are summarized in Table 1, including all dates for which satellite scenes were ordered, aircraft data were acquired, or data were requested but not ordered due to cloudy weather. Based on these data, the following sections address the utility of current satellite- and aircraft-based systems for irrigation management, and an economic assessment of such applications.

Evaluation of current satellite systems for irrigation management

The summary presented in Table 1 gives insight into the utility of current satellite systems for irrigation management purposes. Over the measurement period of June–August, there were 43 possible SPOT and Landsat acquisitions with a maximum time lapse between acquisitions of 5 days. Yet, we were able to obtain only 7 SPOT scenes and 8 TM scenes with a maximum time lapse of 11 days. Though weather is a commonly-cited reason for gaps in data acquisition, only 2 SPOT acquisitions and no TM acquisitions were canceled due to cloudy weather. The majority of non-acquisitions were due to technical problems, these included:

Conflict at receiving station. Due to similar orbital configuration of the Landsat and SPOT satellites and the limitations of the receiving station, there were often occasions of conflict resulting in no data acquisition for our experiment.

Possibility of specular reflectance. Due to the possibility of damage to the system detectors from specular reflectance, it was not possible to order SPOT HRV images when the sensor viewing angle was of opposite sign and within ±5° of the solar zenith angle.

Table 1 Satellite and aircraft data acquisition dates and times, solar and view angles, and weather conditions

Date	DOY[1]	Satellite	Sensor	Overpass time	View angle[2]	Solar angle[2]	Atmos data[3]	Aircraft data[4]	Weather
09 Apr	99	SPOT	HRV-2	11:25	+11.4	−29.7	yes	yes	clear
10 Apr	100	SPOT	HRV-2	11:06	−22.3	−31.8	yes	yes	clear
20 Apr	110	[a]						yes	nearly complete cloud cover
25 Apr	115	[b]						yes	clear
30 Apr	120	SPOT	HRV-1	11:21	+05.3	−23.4			[u]
10 May	130	SPOT	HRV-2	11:29	+18.6	−19.9		yes	spots of cirrus after 11:15
15 May	135	[a]							complete cloud cover
21 May	141	[a]						yes	about 80% cloud cover
26 May	146	SPOT-1	HRV-1	11:21	+04.6	−18.4		yes	clear
31 May	151	Landsat-5	TM	10:34	0	−27.1	yes	yes	clear
31 May	151	[c]					yes	yes	clear
06 Jun	157	SPOT-1	HRV-1	11:10	−15.8	−19.6		yes	clear
16 Jun	167	Landsat-5	TM	10:34	0	−25.7	yes	yes	thin cirrus
16 Jun	167	SPOT-1	HRV-1	11:17	−03.7	−18.3	yes	yes	thin cirrus
21 Jun	172	SPOT-1	HRV-1	11:21	+04.6	−17.6		[d]	cloud-free but hazy
27 Jun	178	[a]						yes	clouds
02 Jul	183	Landsat-5	TM	10:34	0	−27.7		yes	clear over site – cirrus in SE
02 Jul	183	SPOT-1	HRV-1	11:10	−15.8	−20.3		yes	clear over site – cirrus in SE
07 Jul	188	[b]						yes	clear
10 Jul	191	Landsat-4	TM	10:34	0	−28.6			nearly complete cloud cover
12 Jul	193	[b]						yes	clear until after 11:30
18 Jul	199	Landsat-5	TM	10:34	0	−29.1		yes	scattered bright cumulus
18 Jul	199	SPOT-1	HRV-1	11:02	−28.3	−23.4		yes	cumulus dissipated at 11:00
26 Jul	207	Landsat-4	TM	10:34	0	−30.3		yes	cloud-free, some haze
01 Aug	213	SPOT-1	HRV-1	11:33	+24.4	−20.2		yes	clear
03 Aug	215	Landsat-5	TM	10:34	0	−29.8		yes	about 80% cloud cover
07 Aug	219	[a]							many clouds
11 Aug	223	Landsat-4	TM	10:34	0	−32.5		yes	clouds may affect data
12 Aug	224	[e]						yes	clear
17 Aug	229	[f]						yes	clear
19 Aug	231	Landsat-5	TM	10:34	0	−33.5		yes	clear
22 Aug	234	SPOT-1	HRV-1	11:30	+18.2	−25.2		yes	clear
23 Aug	235	[e]						yes	clear
27 Aug	239	[g,f]						yes	clear
28 Aug	240	[f]						yes	clear
04 Sep	247	Landsat-5	TM	10:34	0	−36.7			thin cirrus around sun
07 Sep	250	[e]							clear
12 Sep	255	Landsat-4	TM	10:34	0	−40.0		yes	clear overhead, clouds near
12 Sep	255	[h]						yes	clear overhead, clouds near
28 Sep	271	Landsat-4	TM	10:34	0	−43.2	yes	yes	clear
28 Sep	271	SPOT-1	HRV-1	11:18	−03.7	−37.7	yes	yes	clear
13 Oct	286	SPOT-1	HRV-1	11:30	+18.0	−41.9		yes	cirrus from contrails
23 Oct	296	SPOT-1	HRV-1	11:38	+30.0	−45.0			clear
24 Oct	297	[i]						yes	cloud-free but hazy

[1] DOY refers to day of calendar year 1989
[2] Negative solar angles indicate that the sun was to the east of the site (morning). Negative view angles indicate that the satellite was east of the site and positive angles indicate that it was west of the site
[3] Atmospheric optical depth measurements
[4] Aircraft-based reflectance and temperature measurements
[a] SPOT data not requested because of weather
[b] SPOT data not acquired – conflict at receiving station
[c] SPOT data not acquired – view angle +12°, possibility of specular reflectance
[d] Aircraft data not acquired – complete cloud cover until about 11:00 then cloud-free but hazy
[e] SPOT data not obtained – reason unknown
[f] SPOT data should have been ordered but wasn't
[g] Landsat TM supposedly acquired but tapes missing
[h] SPOT data supposedly acquired but tapes missing
[i] Not known why SPOT data acquired on DOY 296 instead of DOY 297 as scheduled
[u] Unknown

General programming errors. There were occasions when images were not acquired due to simple programming errors. Some images were acquired on the wrong day or at the wrong site or were not programmed for acquisition at all.

An example of the technical problems associated with acquisition of satellite data occurred during the month of July. A SPOT HRV image was acquired on 2 July; the next four possible acquisitions (6, 7, 12 and 17 July) were not obtained due to conflicts at the receiving station. The next successful

HRV image was acquired 16 days later on 18 July. Thereafter, the next four acquisitions (22, 23, 27 and 28 July) were again foiled due to conflicts at the receiving station and the possibility of specular reflectance. Of the 11 possible HRV acquisitions for July, only two images were acquired even though there were no instances of cloudy weather. Furthermore, we found that the two-week delivery schedule was erratic and most images arrived at MAC three to six weeks after acquisition.

Toward the end of June, it was apparent that sufficient images could not be acquired in a timely manner for near real-time evaluation by on-site farm managers. Furthermore, the airborne multispectral video data could not be processed because of insurmountable hardware supply problems. Consequently, the on-site image processing technician returned to ITD earlier than scheduled and the goal of evaluating satellite imagery for day-to-day irrigation management was not fulfilled.

However, despite the technical problems, this experiment resulted in an unprecedented collection of 15 SPOT HRV and 12 Landsat TM images (supported with 36 aircraft overflights) for evaluation of such data for irrigation management. In order to acquire these images, four satellite sensors:, Landsat4-TM, Landsat5-TM, SPOT1-HRV1 and SPOT1-HRV2 were utilized. The images were acquired at solar zenith angles ranging from 17.6° to 45° and the viewing angles of the SPOT data ranged from –28.3° to +30.0°. This multi-sensor, multi-angle, multi-temporal data set exemplifies the challenges to using satellites for irrigation management. The MAC experiment provided the opportunity to address the following scientific issues in relation to irrigation management:

Effects of sun/sensor/target geometry. In an in-depth analysis of the SPOT HRV data acquired during this experiment, Qi et al. (1993) concluded that the influences of atmosphere, view and soil background on vegetation incides and reflectances were intricately coupled and dependent on surface characteristics. They could not find one single component that consistently dominated the variations encountered.

Sensor calibration. Using Landsat and SPOT data acquired at MAC, Holm et al. (1989) and Moran et al. (1990) showed that the sensor calibration was an influential component of the retrieval of surface reflectance factors from satellite digital data, particularly for low reflectance targets (visible wavelengths over dense vegetation). Recently, Thome et al. (1993) and Gellman et al. (1993) documented the significant reductions in responsivity of the HRV and TM sensors over time, and emphasized the need for frequent, in-flight calibrations for all satellite-based sensors.

Atmospheric correction. Pinter et al. (1990) reported that atmospheric variations had a large influence on spectral vegetation indices (e.g., Normalized Difference Vegetation Index (NDVI); Deering et al. 1975) derived from the SPOT HRV images at MAC. In fact, for a spectral band-ratioed vegetation index, they found that the influence of atmosphere was greater than that of viewing angle variation. Moran et al. (1992) tested several simplified techniques for atmospheric correction of MAC Landsat TM data that may be sufficiently accurate for operational irrigation management.

These experimental results suggested that the use of current satellites for irrigation management was technically impractical. The current guaranteed turnaround times of SPOT and TM data with a rush fee are three days and two days, respectively. Jackson (1984) suggested an optimum data delivery time of minutes and maximum time of a few hours.

Two of the technical problems identified in this analysis have been resolved since conducting this experiment in 1989. Conflicts at the receiving station have been resolved by the launch of a new Tracking Data Relay Satellite System (TDRSS) satellite in 1992, and restrictions on SPOT image acquisition due to possibility of specular reflectance have been eliminated as SPOT Image Corp. discerned that the possibility of damage to detectors was minimal. Even with the resolution of these problems and the launch of two new satellites (SPOT2 and SPOT3), we are still far from achieving the frequency of coverage suggested by Jackson (1984); that is, "continuous coverage would be optimum with once a day coverage as a minimum".

Evaluation of remotely-sensed data for irrigation management

The aircraft-based data acquired using the Exotech and Everest radiometers provided the opportunity to assess in retrospect the usefulness of remotely-sensed information for irrigation management. Because the aircraft was flown at a low altitude (100 m above ground level) and all the instruments were calibrated and pointed normal to the surface, these data were unaffected by the three issues identified above for satellite image analysis. The following is a preliminary analysis of the use of spectral vegetation index and surface temperature to identify irrigation patterns and crop evaporative water loss.

Two fields were selected for analysis, one planted with alfalfa and the other with cotton (Fig. 1). For the alfalfa field, data for one harvest cycle and two sites (A and B) were processed for analysis. For cotton, data for the entire growing season and three sites (A, B, and C) were analyzed. The reflectance of the cotton field rises sharply at a distance of 580 – 700 m from the west end of the field (Site B) due to a change from loam to sandy loam soil. This section of the field was expected to have different drainage characteristics than the rest of the field and was therefore selected for analysis. The other sites in the cotton and alfalfa fields were selected based on irrigation patterns in the field throughout the season. For each site, the surface temperature and soil-adjusted vegetation index (SAVI) were computed, where

$$\mathrm{SAVI} = (\rho_{\mathrm{NIR}} - \rho_{\mathrm{red}})/(\rho_{\mathrm{NIR}} + \rho_{\mathrm{red}} + L)\,(1 + L)\,, \quad (1)$$

and ρ_{NIR} and ρ_{red} are the near-IR and red reflectances, respectively, and L is a constant assumed to be 0.5 for a wide

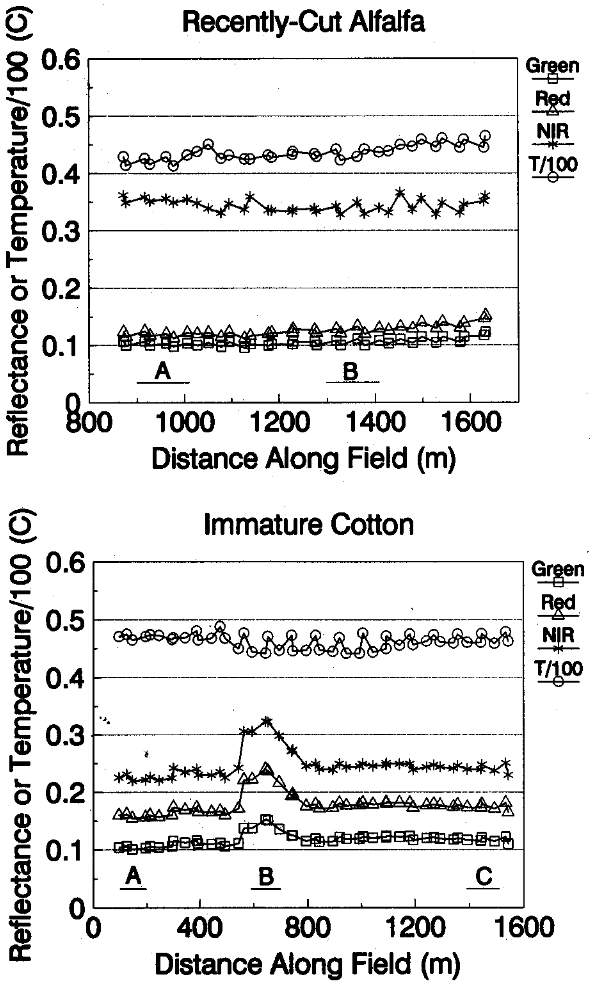

Fig. 1 Aircraft-based measurements of spectral reflectance and temperature (divided by 100) for an alfalfa and cotton field at MAC. Both fields were sparsely vegetated on these dates. The zig-zag pattern along some of the lines is due to the fact that data from two flight lines (approximately 15 min apart) were combined into the one data set presented here

variety of LAI values (Huete 1988). The SAVI was derived to be sensitive to increases in vegetation cover and insensitive to spectral changes in soil background such as soil moisture-related differences.

Background: optical remote sensing for irrigation management

A currently popular algorithms using optical remote sensing for irrigation management is the Crop Water Stress Index (CWSI) which correlates crop water stress with the foliage-air temperature difference (Jackson et al. 1981). In this index the energy balance equation is expressed in terms of foliage-air temperature,

$$(T_c - T_a) = [r_a\,(R_n - G)/C_v]\;[\gamma(1 + r_c/r_a)/\{\Delta + \gamma(1 + r_c/r_a)\}] - [\mathrm{VPD}/\{\Delta + \gamma(1 + r_c/r_a)\}]\,, \quad (2)$$

where T_c is the crop foliage temperature (°C), T_a the air temperature (°C), r_a the aerodynamic resistance (s m^{-1}), R_n the net radiant heat flux density (W m^{-2}), G the soil heat flux density (W m^{-2}), C_v the volumetric heat capacity of air (J °C^{-1} m^{-3}), r_c the canopy resistance (s m^{-1}) to vapor transport, γ the psychrometric constant (kPa °C^{-1}), Δ the slope of the saturated vapor pressure-temperature relation (kPa °C^{-1}), and VPD the vapor pressure deficit of the air (kPa). Equation (2) was then solved for the ratio r_c/r_a which was used in the relation

$$\mathrm{CWSI} = 1 - \Gamma/E\Gamma_p = [\gamma(1 + r_c/r_a) - \gamma^*]/[\Delta + \gamma(1 + r_c/r_a)]\,, \quad (3)$$

where

$$r_c/r_a = \{[\gamma r_a\,R_n/C_v] - [(T_c - T_a)\,(\Delta + \gamma)] - \mathrm{VPD}\}/\{\gamma[(T_c - T_a) - r_a\,(R_n - G)/C_v]\}\,, \quad (4)$$

to obtain the ratio of transpiration Γ to potential evapotranspiration $E\Gamma_p$. The CWSI defined by Eq. (3) was used as an index of crop stress and thus an indicator of when to irrigate.

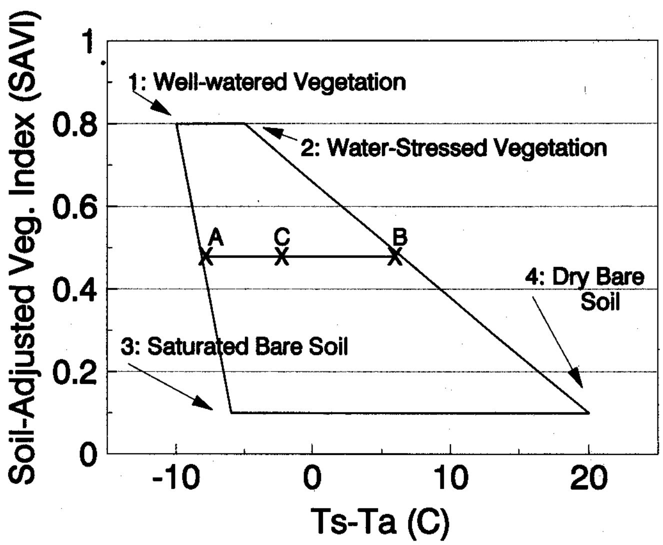

Fig. 2 The trapezoidal shape resulting from the relation between $(T_s - T_a)$ and the fractional vegetation cover (related linearly to the soil-adjusted vegetation index SAVI). With a measurement of $(T_s - T_a)$ at point C, the Water Deficit Index (WDI) is equal to the ratio of distances AC and AB

However, application of CWSI with satellite- or aircraft-based measurements of surface temperature is restricted to fully-canopy conditions when surface temperature is equal to foliage temperature. This limits the usefulness of CWSI for partial crop conditions when irrigation management decisions can be crucial. In response to this, Moran et al. (1994) developed a Water Deficit Index (WDI) which combined SAVI with surface temperature measurements (a composite of both the soil and plant temperatures) to determine field water deficit conditions for partial cover crops. The relation of $T_s - T_a$ and SAVI (for dry and wet soil conditions and for partial- and full-cover canopies) was found to be defined by a trapezoidal shape (Fig. 2). The vertices of the trapezoid corresponded to 1) well-watered full-cover vegetation, 2) water-stressed full-cover vegetation, 3) saturated bare soil and 4) dry bare soil.

This theoretical shape was termed the VIT (Vegetation Index/Temperature) Trapezoid. The left edge of the trapezoid corresponds to T_s-T_a values for surfaces evaporating at the potential rate; the right edge corresponds to T_s-T_a values for surfaces in which no evaporation is occurring. Thus, for a given measurement of T_s-T_a and SAVI (point C in Fig. 2), the ratio of distances CB/AB is equal to the ratio of actual and potential evapotranspiration. Further, WDI is defined as the distance AC/AB, where WDI = 0.0 for well-watered conditions and WDI = 1.0 for maximum stress conditions.

In practice, WDI utilizes the Penman-Monteith energy balance equation to define the four vertices of the VIT Trapezoid that encompasses all possible combinations of SAVI and T_s-T_a for one crop type on one day (Fig. 2). That is, for full-cover, well-watered vegetation,

$$(T_s-T_a)_1=[r_a\,(R_n-G)/C_v]\,[\gamma(1+r_{cp}/r_a)/\{\Delta+\gamma(1+r_{cp}/r_a)\}]-[\mathrm{VPD}/\{\Delta+\gamma(1+r_{cp}/r_a)\}]\,, \quad (5)$$

where r_{cp} is the canopy resistance at potential evapotranspiration and the subscript n of $(T_s-T_a)_n$ refers to vertex n in Fig. 2. For full-cover vegetation with no available water,

$$(T_s-T_a)_2=[r_a\,(R_n-G)/C_v]\,[\gamma(1+r_{cx}/r_a)\}]-[\mathrm{VPD}/\{\Delta+\gamma(1+r_{cx}/r_a)\}]\,, \quad (6)$$

where r_{cx} is the canopy resistance associated with nearly complete stomatal closure. For saturated bare soil, where $r_c=0$ (the case of a free water surface),

$$(T_s-T_a)_3=[r_a\,(R_n-G)/C_v]\,[\gamma/(\Delta+\gamma)]-[\mathrm{VPD}/(\Delta+\gamma)], \quad (7)$$

and for dry bare soil, where $r_c=\infty$ (analogous to complete stomatal closure),

$$(T_s-T_a)_4=[r_a\,(R_n-G)/C_v]\,. \quad (8)$$

Referring to Fig. 2, WDI is operationally equivalent to the CWSI for full-cover canopies (maximum SAVI), where a measurement of surface temperature (T_s) is equivalent to a measurement of foliage temperature (T_c).

The on-site measurements necessary to solve Eqs. (5)–(8) and compute WDI are R_n, VPD, T_a and wind speed. A value of G can be estimated as a function of R_n and percent crop cover (or SAVI) (Clothier et al. 1986). It is also necessary to know the crop type and such characteristics as maximum-possible crop height, maximum-possible leaf area index (LAI), and maximum- and minimum-possible stomatal resistances (r_{sx} and r_{sp}). In many cases, these inputs are known or can be reasonably estimated. These inputs and the assumptions associated with them are discussed in detail by Moran et al. (1994) and will not be addressed here.

The VIT Trapezoid and WDI appear to have potential for evaluating evapotranspiration rate and relative field water deficit for both full-cover and partially-vegetated sites. This represents an advantage over CWSI which was limited in application to full-cover vegetation. Like CWSI, the WDI requires few input parameters in addition to remotely-sensed data, and most input values are either known or can be adequately estimated. This new index, WDI, is

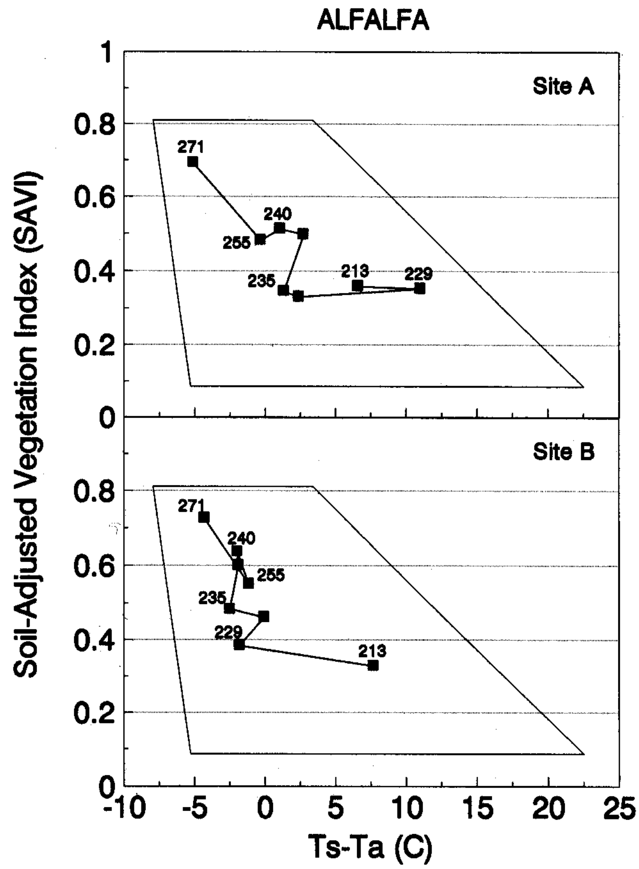

Fig. 3 Values of SAVI and surface-air temperature (T_s-T_a) for sites A and B in the alfalfa field. The numbers within the graph represent the day of year the values were measured (some dates are not listed for graphic clarity). The trapezoidal shape represents the limits of these values based on daily meteorological and crop data (Moran et al. 1994)

evaluated as a tool for irrigation management using the aircraft-based measurements of the alfalfa and cotton fields at MAC in the following section.

WDI application: alfalfa

A comparison of the T_s-T_a and SAVI data for the two sites within the alfalfa over the harvest period illustrates the sensitivity of these measurements to irrigation practices and vegetation growth (Fig. 3). Theoretically, for a constant SAVI value, the proximity of any point to the left or right limits of the Vegetation Index/Temperature (VIT) trapezoid would indicate more or less available water, respectively. On day of year (DOY) 213, the SAVI and T_s-T_a of sites A and B were very similar. On DOY 229, site B was irrigated and site A was not. This resulted in a shift of site B data upward and to the left within the VIT trapezoid, indicating a slight increase in vegetation and substantial decrease in T_s-T_a from DOY 213. Site A was irrigated with the same amount of water several days later. However, it is apparent that the surface temperature of site A remained higher (and the SAVI remained lower) than that of site B for the next two weeks. This lag could be an indication of lower plant yield due to the late irrigation. Finally, by DOY 271, the two sites within the field had nearly identical SAVI and $T_s - T_a$ values. This could indicate that the crop at site A was able to recover later in the harvest cycle.

Computations of WDI for sites A and B of the alfalfa field reflect the results of differing irrigation practices (Fig. 4). WDI of site A is nearly equal to 1.0 on DOY 229, just prior to irrigation; whereas, the recent irrigation of site B on the same day resulted in a WDI value close to zero. The resultant lag in the vitality of the crop at site A is also apparent in the values of WDI. However, the two sites have a nearly identical WDI at the end of the growing season. Unfortunately, the differences in crop stress for these two sites cannot be quantified because leaf turgor and soil moisture measurements were not made during this experiment.

WDI application: cotton

The SAVI and $T_s - T_a$ for the cotton field exemplify the typical cotton growing pattern. The SAVI increased (and $T_s - T_a$ decreased) from DOY 130 to DOY 225 and then began to decline (and $T_s - T_a$ to increase) as the crop senesced (Fig. 5). A defoliant was applied just prior to DOY 286, resulting in a rapid decline in SAVI. The east end of the field (site C) was irrigated on DOY 151. Site B was irrigated on DOY 157 and site A was irrigated several days later. These irrigations are indicated by an extreme decrease in $T_s - T_a$ with little change in the SAVI.

Another irrigation started on the east end of the field (site C) on DOY 188; the other cotton sites were subsequently irrigated between DOY 189 – 193. It is notable that for near full-cover canopies (site C, DOY 188), the effect of irrigations on $T_s - T_a$ is less substantial than for sparsely-vegetated sites (site C, DOY 151). This difference is incorporated into the trapezoidal shape, where the top of the

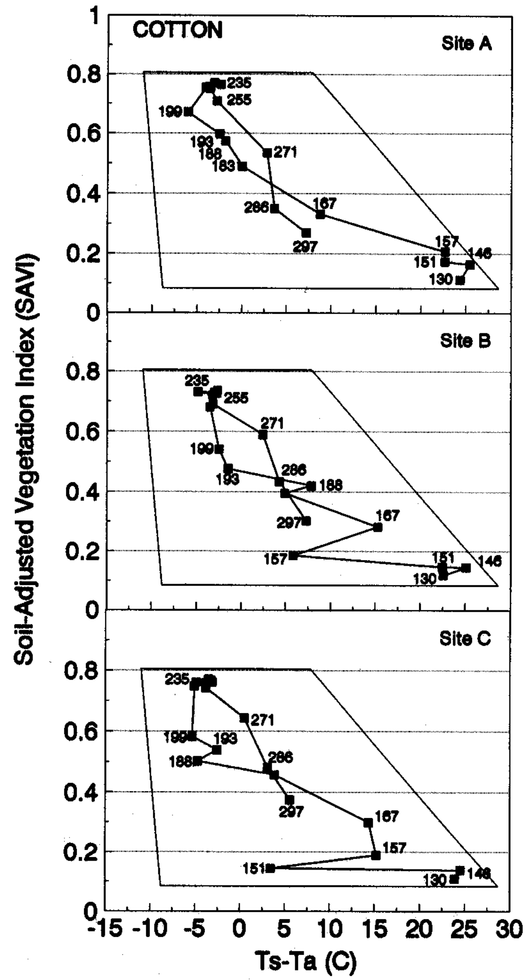

Fig. 5 Values of SAVI and the surface-air temperature ($T_s - T_a$) for sites A, B and C in the cotton field. As in Fig. 3, the numbers within the graph represent the day of year and the trapezoidal shape represents the limits of these values based on seasonal meteorological and crop data

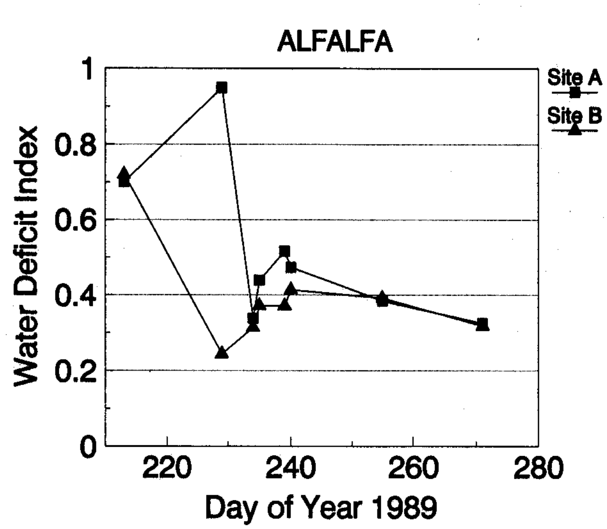

Fig. 4 Values of Water Deficit Index (WDI) for sites A and B in the alfalfa field over a single harvest period. A WDI value of 0.0 indicates well-watered conditions and a value of 1.0 indicates maximum stress conditions

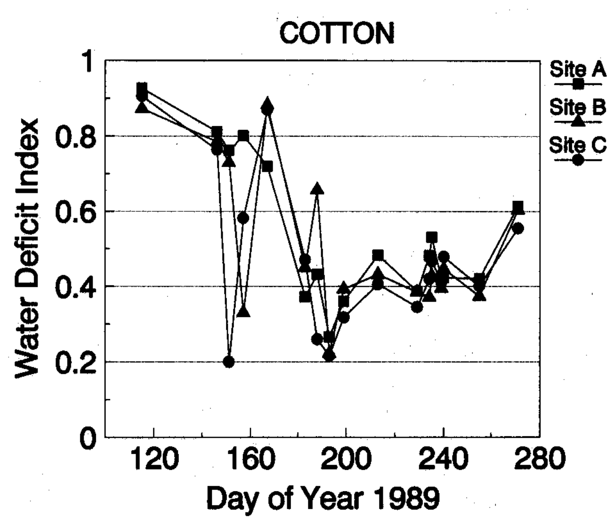

Fig. 6 Values of Water Deficit Index (WDI) for sites A, B and C in the cotton field over a single growing season

Table 2 Cost/benefit analysis of the use of satellite- or aircraft-based remote sensing for irrigation management of cotton in an irrigation district in Arizona

Benefits to farmer	
Cost of water ($/ha-m)	$ 321.00
Depth of irrigation (m)	0.13/irrigation
Cotton hectarage (ha)	16,188
Number of irrigations saved	2
Total benefit	($ 321×0.13×16,188×2) = $ 1,351,050
Costs based on satellite images (OPTION 1)	
Cost of landsat TM image	$ 13,200.00
Number of TM images	52/season
Length of growing season	183 days
Total cost of images	($ 13,200×52) = $ 686,400.00
Salary of technician	$ 30,000.00
Cost of image production [a]	$ 30,000.00
Total cost	($ 686,400 + $ 30,000 + $ 30,000) = $ 746,400.00
Costs based on aircraft images (OPTION 2)	
Cost/month/hectare	$ 12.36 [b]
Months	6.1
Total cost	($ 12.36×6.1×16,188) = $ 1,220,017.00
Cost and benefit summary	
	Net benefit
OPTION 1: satellite	($ 1,351,050 − $ 746,400) = $ 604,650
OPTION 2: aircraft	($ 1,351,050 − $ 1,220,017) = $ 131,033

[a] Note that the start-up costs associated with the satellite processing task are not included in this analysis and could run as high as $ 100,000

[b] Personal communication with Dr. D. J. Garrot Jr of Agrometrics, Inc., Tucson, Arizona, regarding costs for helicopter-based reconnaissance on a bi-weekly basis and subsequent image processing. Trade names and company names are included for the benefit of the reader and do not constitute endorsement by the U.S. Department of Agriculture

VIT trapezoid is narrower than the base. Consequently, the WDI of site C (Fig. 6) is very low on DOY 188 and WDI of the other sites are high; particularly the sandy site B. Then, after the field irrigation is completed (DOY 193), the WDI of all sites is similarly low.

It is also notable that site A was the last section of the field to receive irrigation early in the season, resulting in high WDI values prior to DOY 167. Site A also has the highest WDI of all sites late in the season (after DOY 199). There appears to be potential to use the WDI to identify areas of early season water stress that could result in late-season decreases in yield.

Economic assessment

Indices such as CWSI and WDI show promise for use in scheduling irrigations of both sparsely- and densely-vegetated fields. Both CWSI and WDI require few input parameters in addition to remotely-sensed data, and most input values are either known or can be adequately estimated. With recent technological breakthroughs in low-cost digital imaging systems, affordable high speed computers and global positioning systems (GPS), it may be possible to utilize low-altitude aircraft-based systems for daily irrigation scheduling. However, the cost of such sensors can be over $ 100,000 and the cost of each flight (assuming plane rental and pilot salary) can be $ 500/day. At this time, the standard TM product costs $ 4400 with a delivery time of one to three weeks; a seven-day turnaround can be purchased for 1.5 times the image cost or a two-day turnaround for three times the image cost. The standard HRV product costs $ 3050 with a delivery time of two to three weeks; for a rush fee of $ 1500, the product can be delivered in 48 h. For individual farmers, these costs are prohibitive. For large irrigation districts in arid and semi-arid regions, these costs may appear more reasonable.

A simple cost/benefit analysis for the Maricopa-Stanfield Irrigation and Drainage District (IDD) in Arizona is included in Table 2. Maricopa-Stanfield IDD (which encompasses MAC) consists of approximately 35,208 ha, of which cotton was grown on about 16,188 ha during 1993. A typical growing season might extend from the planting date of 1 April to the defoliation date of 15 September i.e. 183 days. Growers will generally apply nine to ten irrigations of 13 cm during a growing season. The cost of water at MAC during 1993 was $ 321.00 per ha-m.

In addition to the assumptions listed above and those inherent in the data of Table 2, the scenario for this cost/benefit analysis was based on the following assumptions:

1. All growers in the Maricopa-Stanfield IDD that grow cotton (totalling 16,188 ha) will schedule their irrigations using results of remote sensing analysis;

2. Each grower will be able to save two irrigations of 13 cm each based on remote sensing techniques and will not incur a loss of yield by doing so (Husman et al. 1991);

3. In Option 1, the processing of Landsat TM images will be accomplished by a technician working for an or-

ganization totally encompassing the IDD, whose salary and image production costs are taken into account in this cost analysis (start-up costs were not included);

4. In Option 2, the acquisition and processing of aircraft-based images will be accomplished by an organization dedicated to providing farmers with such information; and

5. Processed images of CWSI or WDI will be provided to farmers with 48-hour turnaround twice per week.

According to the results presented in Table 2, the Maricopa-Stanfield IDD would benefit from the use of satellite or aircraft imagery for irrigation scheduling. If Landsat TM imagery were available twice per week (which it currently is not), the net profit in a single season could be as large as \$ 604,650 per year (or about \$ 37/ha). At this time, it is *possible* to obtain aircraft-based images on a biweekly basis over some irrigation districts; the profit obtained using such imagery could be as large as \$ 131,033 (\$ 8/ha). If only one irrigation were saved instead of two using the aircraft-based images, the irrigation district would experience a loss of \$ 544,492 (\$ 33/ha).

This cost/benefit scenario was based on the assumption that satellite or aircraft imagery would be available twice per week, an optimistic assumption when weather conditions and technical problems are considered. An alternative that is currently being used to circumvent the need for regular overflights is to combine less-frequent remotely sensed measurements with crop growth simulation models based on meteorological data to produce daily estimates of crop water status (e.g., Maas et al. 1992; Bausch 1989; Bausch and Neale 1989). In such models, meteorological and agronomic data are used to make continuous predictions of plant development, and remote sensing inputs are used whenever available to correct the models to actual conditions. This combined modeling/remote sensing approach could become a valuable tool for resource managers in conducting operational, near real-time monitoring of regional water resources and crop yield at a reasonable cost.

Conclusions drawn from this simple cost/benefit analysis should be tempered with consideration of the whole water management issue. Given that water management is a complicated issue encompassing more than just irrigation scheduling, this simple cost/benefit analysis addresses only a part of the economic picture. The potential cost benefits achieved using remote sensing for irrigation scheduling must be weighed against the uncertainties associated with water availability and application.

Conclusions

The ITD objective of evaluating the use of satellites for farm management was not realized. Midway through the growing season it became obvious that satellite data could not be obtained as often as expected due to technical shortcomings in the satellite systems and even when images were acquired, the two-week delivery time could not be met. Due to these shortcomings, the on-site ITD personnel returned home early. The experiment was continued without them and thus without hopes of presenting images to farm managers for near real-time interpretation.

However the experiment was successful in evaluating the research issues associated with use of satellite data for irrigation management. Analysis of this data set in combination with other data acquired at MAC resulted in substantial progress in understanding the issues of sun/sensor/target geometry (Qi et al. 1993; Pinter et al. 1990), sensor calibration (Holm et al. 1988; Moran et al. 1990), and atmospheric correction (Moran et al. 1992). The experiment also resulted in an exceptional set of aircraft-based spectral data that were used in this paper to evaluate the utility of surface reflectance and temperature measurements for detecting irrigation patterns and field water deficit conditions. A spectral Water Deficit Index (WDI) was developed which showed promise for use in scheduling irrigations of both sparsely- and densely-vegetated fields.

The cost/benefit analysis for the use of remotely sensed images for cotton crop irrigation scheduling in the Maricopa-Stanfield irrigation district was encouraging. Assuming water was available as requested by the grower, substantial net profits could be achieved through application of WDI and CWSI for irrigation scheduling. Though only two options were explored, the exclusive use of satellite- or aircraft-based images, it would be possible to achieve even higher profits if a combination approach were used to merge information from satellite- and aircraft-based sensors with crop growth simulation models based on available meteorological data (Moran et al. 1994b).

Despite the technological advances made since Park's scenario was published (Park et al. 1968), very little progress has been achieved in designing, building and launching a commercial satellite system. Until a fleet of satellites dedicated to agriculture are launched, there is no hope of meeting the requirements for an ideal farm management system suggested by Jackson (1984); that is:

Timeliness: optimal data delivery time of minutes and maximum time of a few hours;

Frequency of coverage: Continuous coverage would be optimal with once a day coverage as a minimum; and

Spatial resolution: 5×5 m would be optimal, with 20×20 m acceptable.

Acknowledgements The experiment described here was the coordinated effort of scientists, technicians and students too numerous to mention from Institute for Technology Development (ITD), U.S. Water Conservation Laboratory (USWCL) and the University of Arizona Optical Science Center (OSC) and Dept. of Soil and Water Science (SWS). The original concept and funding were provided by George May (ITD). The organizers of the USWCL effort included Ray Jackson, Tom Clarke and Paul Pinter Jr.; organizers of the OSC effort included Phil Slater, Stuart Biggar and David Gellman; and organizers of the SWS effort included Alfredo Huete and Qi Jiaguo. We all thank the personnel of SPOT Image Corp. and EOSAT Corp. for helping us with this endeavor, and as always, we greatly appreciate the efforts of the staff at MAC to accommodate us in every way possible.

References

Bausch WC (1989) Computerized irrigation scheduling using spectral feedback. In: Dood VA, Grace PM (eds) Proc 11th Intl Cong on Agric Engineering. AA Balkema Publishers, Rotterdam, The Netherlands 1: 561–568

Bausch WC, Neale CMU (1989) Spectral inputs improve corn crop coefficients and irrigation scheduling. Trans ASAE 32: 1901–1908

Clothier BE, Clawson KL, Pinter PJ Jr, Moran MS, Reginato RJ, Jackson RD (1986) Estimation of soil heat flux from net radiation during the growth of alfalfa. Agric For Meteorol 37: 319–329

Deering DW, Rouse JW Jr, Haas RH, Schell HH (1975) Measuring "forage production" of grazing units from Landsat MSS data. Proc 10th Intl Symp of Rem Sens Environ, ERIM, Ann Arbor, Michigan, pp 1169–1198

Gellman DI, Biggar SF, Thome KJ, Slater PN, Moran MS, Dinguirard M, Henry P (1993) A review of SPOT-1 and -2 calibrations at White Sands from launch to present. Proc Soc of Photo-Optical Instrum Eng Symp, 12–16 April, Orlando, Fl, pp 118–125

Holm RG, Moran MS, Jackson RD, Slater PN, Yuan B, Biggar SF (1989) Surface reflectance factor retrieval from Thematic Mapper data. Rem Sens Environ 27: 47–57

Huete AR (1988) A soil-adjusted vegetation index (SAVI). Rem Sens Environ 25: 89–105

Husman SH, Garrot DJ Jr, Moore M (1991) Water stress effects on Upland Cotton lint yields using infrared thermometry to schedule irrigations. Cotton Report, College of Agriculture, University of Arizona, Tucson, Arizona, Series P-87: 111–113

Jackson RD (1984) Remote sensing of vegetation characteristics for farm management. SPIE Rem Sens 475: 81–96

Jackson RD, Idso SB, Reginato RJ, Pinter PJ Jr (1981) Canopy temperature as a crop water stress indicator. Water Resour Res 17: 1133–1138

Maas SJ, Moran MS, Jackson RD (1992) Combining remote sensing and modeling for regional resource monitoring, Part II: A simple model for estimating surface evaporation and biomass production. ASPRS/ACSM/RT'92 Convention: Mapping and Monitoring Global Change, 3–8 August, Washington, DC, pp 225–234

Moran MS, Clarke TR, Inoue Y, Vidal A (1994) Estimating crop water deficit using the relation between surface-air temperature and spectral vegetation index. Rem Sens Environ (in press)

Moran MS, Jackson RD, Hart GF, Slater PN, Bartell RJ, Biggar SF, Gellman DI, Santer RP (1990) Obtaining surface reflectance factors from atmospheric and view angle corrected SPOT-1 HRV data. Rem Sens Environ 32: 203–214

Moran MS, Jackson RD, Slater PN, Teillet PM (1992) Evaluation of simplified procedures for retrieval of land surface reflectance factors from satellite sensor output. Rem Sens Environ 41: 169–184

Park AB, Colwell RN, Meyers VF (1968) Resource survey by satellite; science fiction coming true. Yearbook of Agriculture, pp 13–19

Pinter PJ Jr, Jackson RD, Moran MS (1990) Bidirectional reflectance factors of agricultural targets: a comparison of ground-, aircraft- and satellite-based observations. Rem Sens Environ 32: 215–228

Qi J, Huete AR, Moran MS, Chehbouni A, Jackson RD (1993) Interpretation of vegetation indices derived from multitemporal SPOT images. Rem Sens Environ 44: 89–101

Thome KJ, Gellman DI, Parada RJ, Biggar SF, Slater PN, Moran MS (1993) In-flight radiometric calibration of Landsat-5 Thematic Mapper from 1984 to present. Proc Soc of Photo-Optical Instrum Eng Symp, 12–16 April, Orlando, Fl, pp 126–130